♦ Appendix B. Further Examples of Conceptual Models

Landscape Level Model

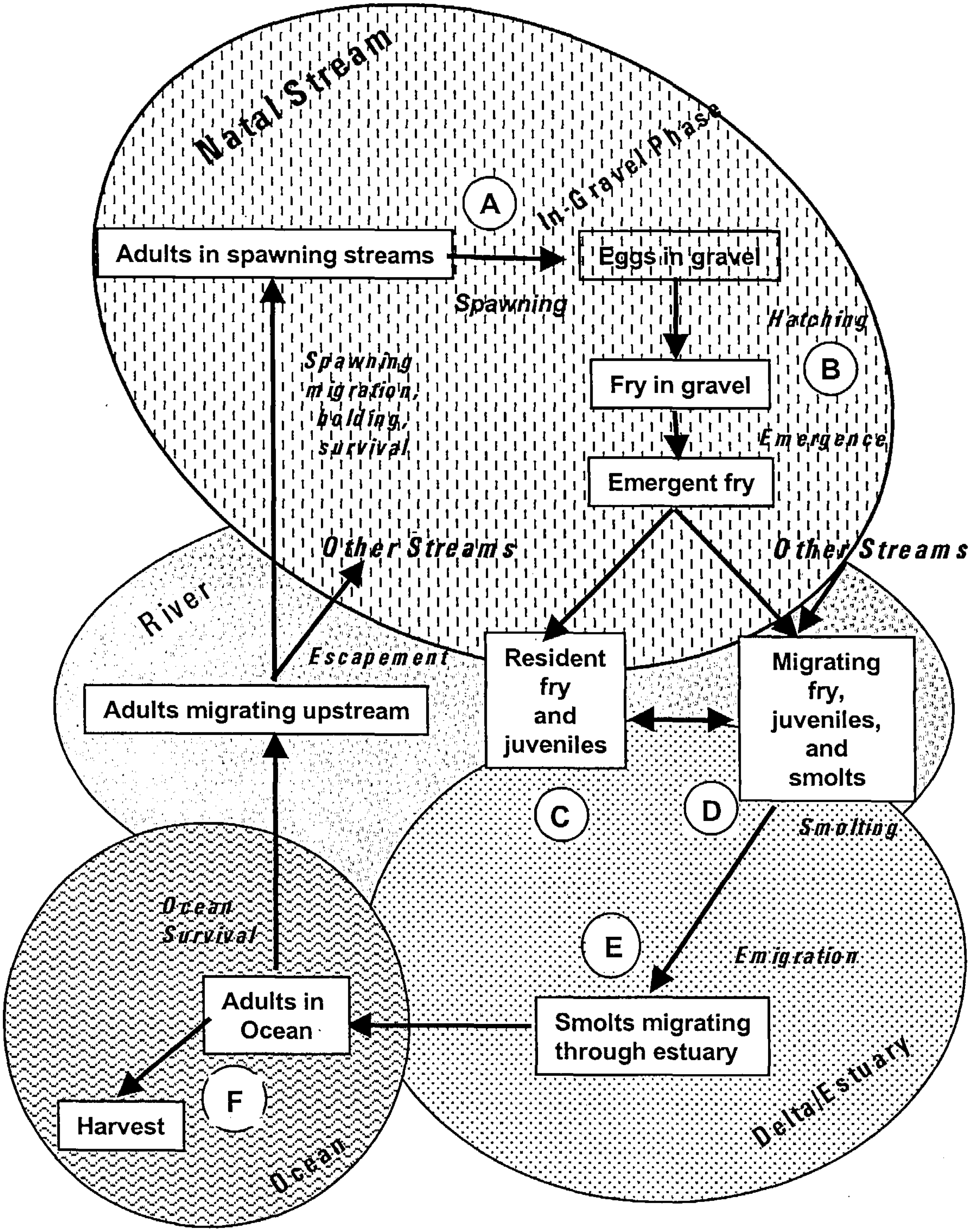
Figure B-1 illustrates a landscape level conceptual model. This model applies to chinook salmon, but its principles also could be applied to striped bass, other anadromous fish, and several species that spawn in the coastal ocean and rear in the estuary. These species link the system across boundaries by migrating between the rivers and the estuary or between the estuary and the ocean. Through their migrations, they expose themselves to variable human and environmental forces well outside the boundaries of the Bay-Delta ecosystem. The principal landscape level issue for managing these populations is the relative importance of events in each region in affecting their abundance. For example, chinook salmon experience rigorous conditions in their spawning and freshwater nursery regions, during migration through the Delta, and in the ocean. If the Delta causes a substantial fraction of their mortality, the opportunity exists for restoration that will be effective in reducing mortality and increasing salmon production. On the other hand, if mortality in the Delta is small, restoration of conditions there may have little effect on salmon production. Similar issues exist for the other species although the lack of direct human influence on oceanic conditions (except harvest) limit the opportunities for restoration in that region. A detailed example of ecosystem restoration for chinook that makes use of this model is discussed in Appendix C.

Conceptual Model of Entrainment

We present two alternative conceptual models of how anadromous fish can be entrained in the state and federal water projects under low-flow conditions (Figure B-2). The upper part of the figure shows schematic maps of the Delta with the key nodes identified at which water and anadromous species diverge into separate pathways. Conceptual model A is the "old" model, in which the emphasis is on net flow. Water moves downstream in the rivers and either toward the ocean or toward the pumps in the Delta, including a landward net flow in the lower San Joaquin River ("QWEST").

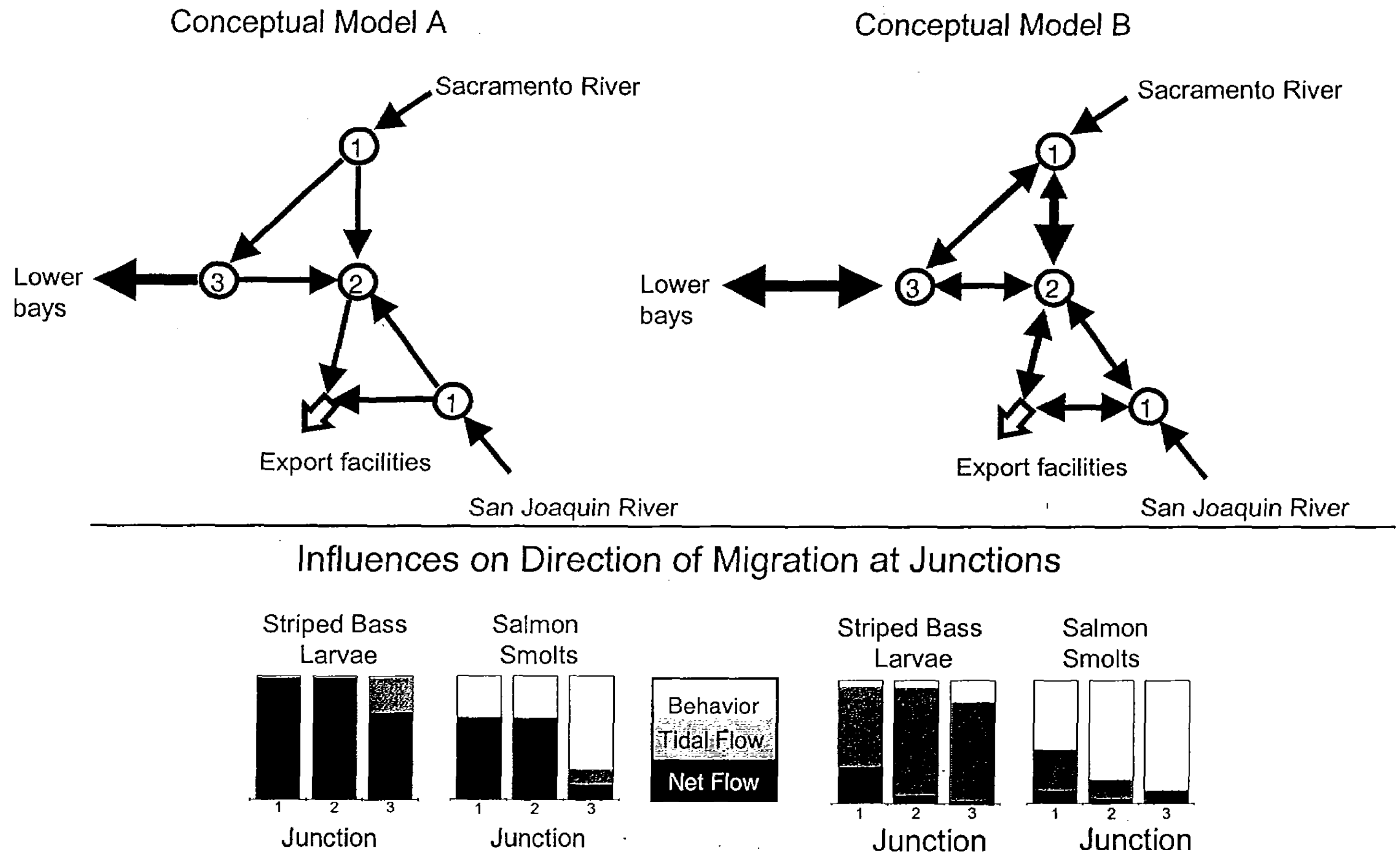
Conceptual model B is based on more recent developments in understanding of hydrodynamics of the Delta and on the realization that fish are not passive particles but are capable of quite complex behavior. Flow in the rivers is downstream, but as we move into the Delta, the flow becomes increasingly dominated by tides. The further west in the Delta we go, the more important the tides are and the less important is riverflow in terms of instantaneous velocity. For example, at Chipps Island under low-flow conditions, net flow is only 1-2% of tidal flow. The bottom panel in Figure B-2 illustrates how the selection of models determines the factors influencing the proportions of fish that take one course or another at each of the numbered nodes in the upper panel. Starting from the left-most bar chart, according to conceptual model A, striped bass larvae are largely subject to net flow, with tides affecting them to some degree at the confluence of the rivers (node 3). Salmon smolts, by contrast, are affected more by their own behavior. Still, the major influence is net (river) flow. Under conceptual model B, by contrast, striped bass larvae are affected mainly by tidal flows and to a lesser extent by net flows. Furthermore, the influence of net flows is nearly gone by the time the larvae reach node 3 (i.e., the low-salinity zone, which under low-flow conditions in late spring is at about the confluence). Behavior of the larvae plays an important role in this model, particularly when they reach brackish water and begin to migrate vertically.

In model B, the fate of salmon smolts is governed primarily by whether they migrate along the shore or distributed across the river. If they migrate



Note: The four oval areas represent the four major geographic regions. Arrows indicate a change of state of surviving salmon, with only ocean harvest mortality displayed explicitly. Terms in italics indicate the major transformations occurring in each phase.

Figure B-1: Landscape Level Conceptual Model of Chinook Salmon



Note: Arrows and circles comprise a schematic of the Delta, with the circles representing key nodes where flow and fish diverge. Single arrows indicate river inputs, and double arrows indicate flows that are partly or mostly tidal, with the sizes of the arrowheads reflecting relative flow velocities for each location. Conceptual model A depicts net flows, with arrows indicating how fish would move under the influence of these flows. Conceptual model B illustrates how water moves in response to both tides and net flow. Fish move under the influence of these flows and their own behavior. Bar charts in the bottom panel illustrate how these conceptual models differ in their prediction of the relative influence of fish behavior, tidal flow, and net flow on the proportion of fish taking alternative pathways at each of the nodes.

Figure B-2: Alternative Conceptual Models of Flow and Fish Movement in the Delta under Low-Flow, High-Export Conditions along the shore, they are more vulnerable to diversions such as at the Delta Cross-Channel than if they are distributed across the channel. In addition, we assume that, like other organisms living in tidal environments, salmon smolts are exquisitely sensitive to the tidal movements and phasing and are capable of moving downstream rapidly using the tidal currents. At the more landward modes, therefore, tidal flow rather than net flow has the most influence on smolt movement patterns.

These alternative models make radically different predictions about the effects of entrainment on salmon and the most effective measures to minimize these effects (Figure B-2). According to model A, losses can be minimized by reducing exports and maximizing flow. Moving the intake up into the Sacramento River would have a clear benefit. According to model B, on the other hand, export flows are not very important in killing salmon, and the most important issue is the strength of the environmental cues available to guide the salmon to sea. Note that this model is more consistent with recent statistical modeling results, which do not find that variation in salmon smolt survival is statistically related to export flows (Newman and Rice in prep.).

For young striped bass, model A again predicts that increasing flow and reducing exports would increase early survival. Model B, on the other hand, predicts a probability of entrainment that depends on the initial position of the fish and the strength of tidal and net flows, including export flows. The further seaward the larvae, the less likely it is to be entrained. Moving the salt field seaward (i.e., moving X2 seaward) reduces the exposure of the fish to entrainment and is therefore more effective than curtailing exports. Note the sharp contrast in the two models' predictions of the effects of moving the intake site.

For delta smelt, the picture is less clear. Under model A, minimizing exports is very important, and moving the intake facility would be very helpful for the species. Minimizing the ration of exports to inflows is believed to reduce the proportion of the smelt population that is entrained. Under model B, X2 determines the position of the bulk of the population and, therefore, the exposure to entrainment, while variation in export flow has little effect unless X2 is far upstream. Thus, moving the intake facility would have little effect except under very low-flow conditions.

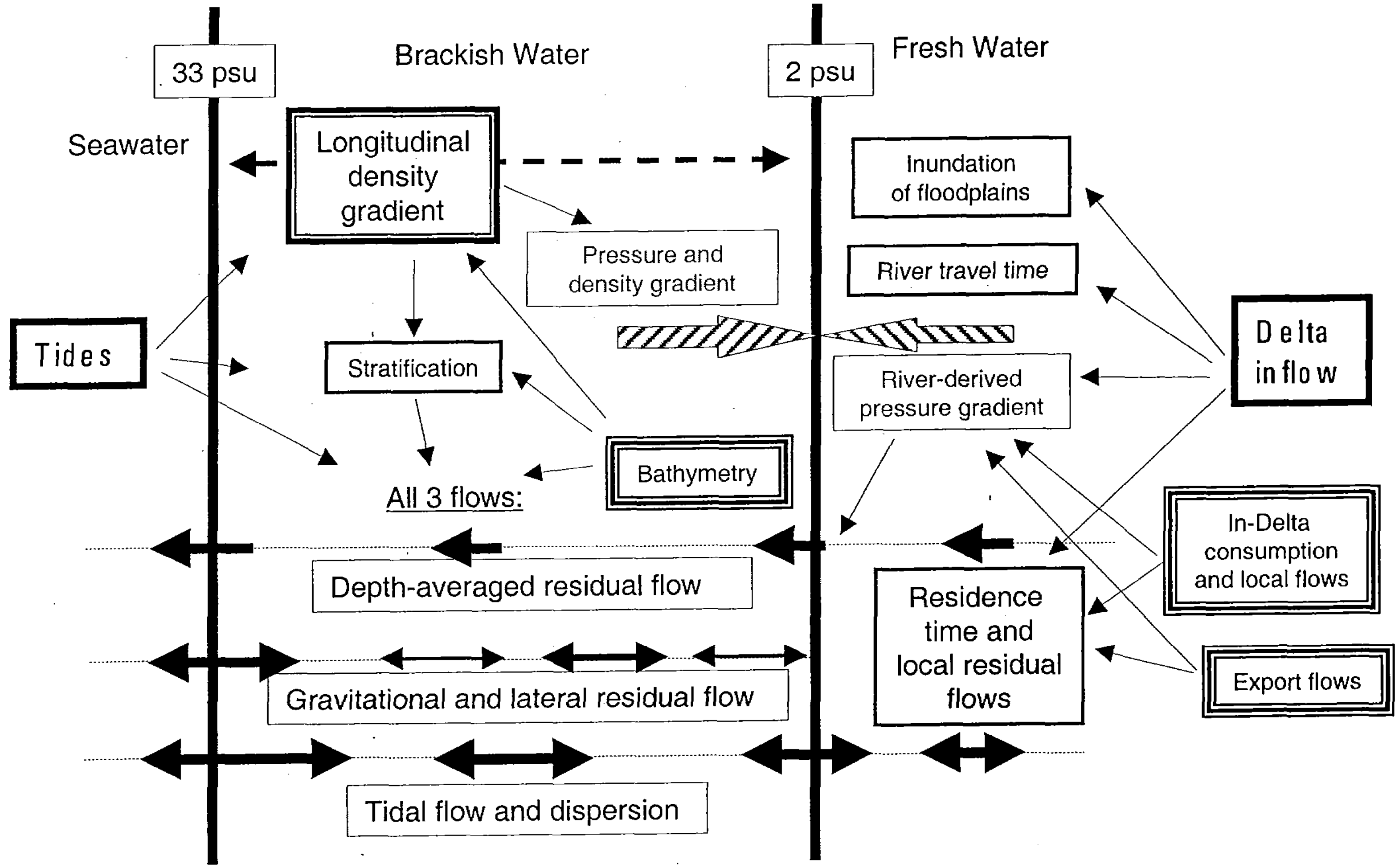
These models, along with the findings of the Diversion Effects on Fish Team (1998), suggest that we have a great deal to learn about entrainment effects before a decision can be made on the construction of large-scale water transfer facilities.

Model of Contrasting Mechanisms Underlying X2 Relationships

In this section, we contrast two mechanisms believed to be important for species that enter the estuary from the ocean as young or spawn in the lower bays and rear in the estuary. These models look in more detail at aspects of the Fish-X2 relationship described in the main body of the text. The two mechanisms are gravitational circulation and extent of physical habitat for rearing.

Recent developments in understanding of the physical characteristics of the estuary have altered our perception of how biota use their environment (e.g., Burau 1998 in Kimmerer 1998). Figure B-3 provides a conceptual model of estuarine circulation patterns designed to illustrate these concepts. For the purposes of this exercise, the main points are as follows. Flow in the brackish parts of the estuary can be considered to have three components as illustrated. First, there must be a cross-sectionally averaged residual (i.e., averaged over the tides) flow to seaward that is equal to the river flow. Second, vertical and lateral asymmetries in residual flow occur through the interaction between stratification, tides, and bathymetry. Third, the strongest flows in most of the estuary are reversing tidal flows, which induce strong longitudinal and lateral dispersion.

Freshwater flow introduces a pressure or level gradient that directs water seaward through the estuary. At the same time, tides drive the denser ocean water into the estuary through a combined pressure and density gradient. These opposing forces determine the length of the salinity gradient and therefore the density gradient. High



Notes: Freshwater inflow and tides are the major forcing functions. The principal role of freshwater input is in setting up a pressure (level) gradient along the axis of the estuary, which forces the depth-averaged residual flow throughout the estuary. Tides introduce a pressure gradient that varies in time, and the salinity gradient attributable to tidal mixing between fresh water and saltwater sets up a density gradient. This interacts with tidal mixing and bathymetry to produce various degrees of stratification and gravitational circulation.

psu = practical salinity units.

Figure B-3: Conceptual Model of Flow Effects with Emphasis on the Brackish Parts of the Estuary freshwater flow over a period of time compresses the longitudinal density gradient, enhancing stratification and possibly gravitational circulation. The opposing density gradient acts like a compressed spring, moving salt landward when freshwater flow (and the accompanying pressure gradient) declines.

Gravitational circulation (Figure B-4) can occur throughout the estuary if stratification occurs. This happens primarily in deep regions, such as beneath the Golden Gate Bridge, in the main channel through northern San Francisco and San Pablo Bays, and in Carquinez Strait. It is rare in the main channel of Suisun Bay (Burau 1998 in Kimmerer 1998). We assume (this theory has not been tested) that stratification is stronger when freshwater input is high because of the compression of the longitudinal density gradient (Figure B-3). Under low-flow conditions (Figure B-4, top), stratification is slight. Near-bottom currents are weaker than near-surface currents. Surface currents are stronger on the ebb than on the flood, whereas bottom currents are stronger on the flood than on the ebb. When freshwater flow is high, the density gradient is compressed and stratification is stronger, causing gravitational circulation to intensify. Under these conditions, the asymmetry in ebb-flood currents is greater, particularly near the bottom.

Certain species of bay organisms may use gravitational circulation to enter the estuary and to move landward. This is a common mode of transport for flatfish, crab, and shrimp larvae (e.g., Cronin and Forward 1979). Essentially, all they need to do is move down in the water column, and gravitational circulation will take them landward. Presumably, the stronger the gravitational flow the more rapid the movement and the larger the abundance of animals that will arrive at the rearing habitat. If correct, this model could explain the X2 relationships for bay shrimp, starry flounder, and possibly Pacific herring.

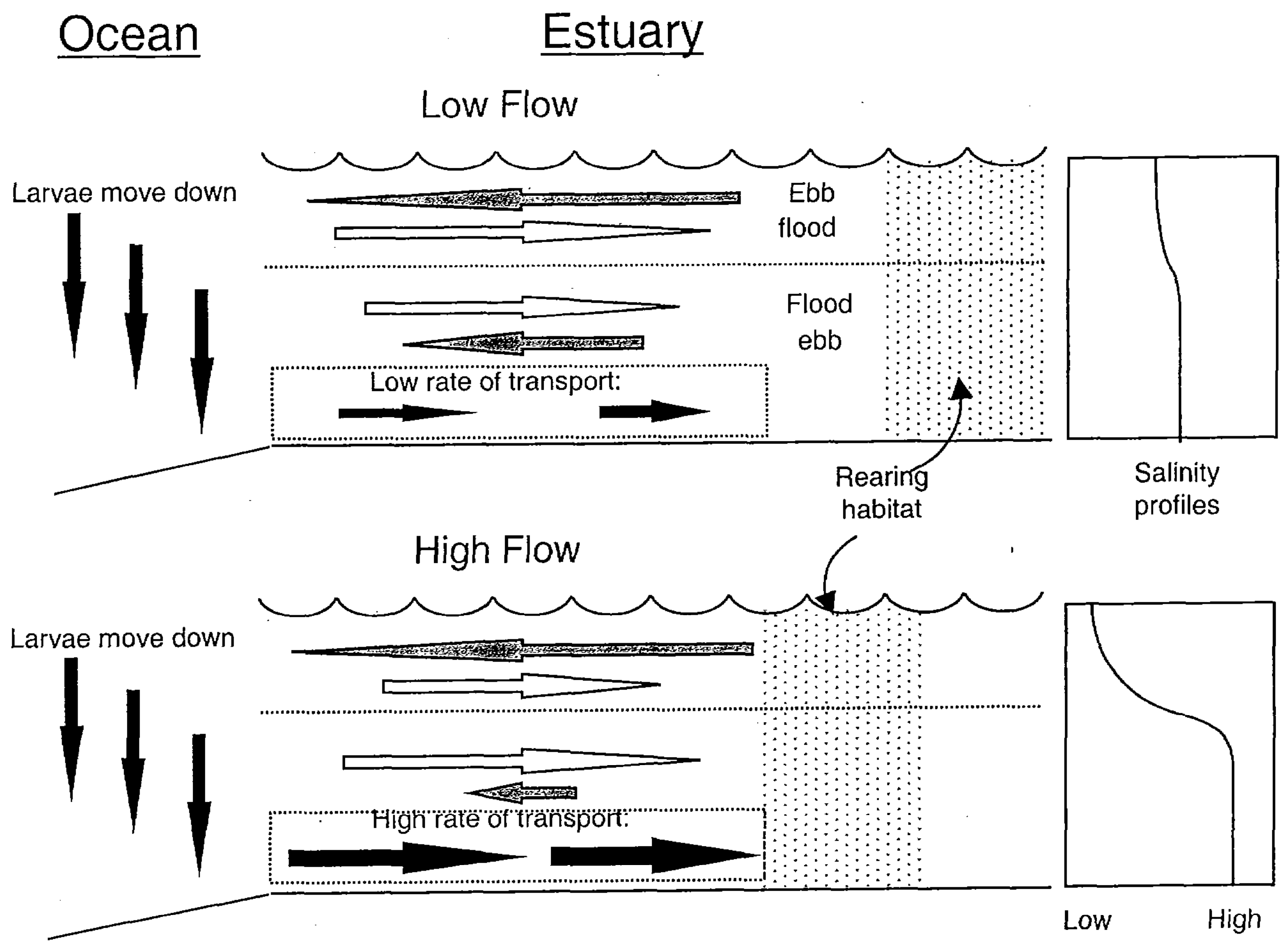
The alternative model holds that the physical extent of nursery habitat increases with increasing flow. This model is supported by a preliminary analysis of the area in the estuary encompassed by selected salinity values (Unger 1994). If habitat is limiting the development of some populations, and if it does indeed increase with flow, then this too could explain the observed relationships.

Actions to protect and enhance the abundance of these species that correlate with X2 (and the predatory species that depend on them) differ depending on which mechanism is most important. If the most important mechanism is gravitational circulation, little can be done to enhance these populations other than to increase freshwater flow (note that dredging channels also may accomplish this, but an additional result may be greater salt penetration). However, if limiting habitat is the key issue, then it may be possible to provide more, better, or more accessible habitat and achieve a suitable level of protection or enhancement with the same or less flow.

Conceptual Model of Meander Migration in a Regulated River

This conceptual model (Figure B-5) illustrates factors influencing meander migration, habitats created as a consequence of migration, and influence of management actions. River meanders migrate through a combination of eroding the outside (concave) bank and simultaneously depositing a point bar on the opposite (convex) bank. The highest velocity flows are concentrated on the outside of the bend, and a pool forms at the outside of the meander bend. Right and left bends alternate, with the highest current shifting from one side of the channel to the other at the "crossover" point between bends, where a gravel riffle forms (Figure B-6). As the meander bend migrates across the valley bottom, the channel dimensions remain essentially constant because erosion of the outside bend is compensated for by deposition on the point bar.

The process of meander migration is ecologically important because it creates and maintains channel and floodplain forms with a diversity of habitats (e.g., undercut banks, overhanging vegetation, scour pools, gravel riffles), delivers large woody debris to the channel, and maintains a diverse assemblage of riparian vegetation at different succession stages. As the outside bend erodes, late-stage successional riparian trees are typically eroded and fall into the channel, providing large



Note: Several species recruit from outside the estuary and must enter the bay to reach nursery areas; some other species reproduce in the bay but then move up the estuary for rearing. Tidal flows in the low-salinity and high-salinity layers are shown as arrows, with gray representing ebb and white representing flood. Black arrows indicate larval movement. Under low-flow conditions, stratification and gravitational circulation are weak; landward transport of larvae is slow. High flow compresses the longitudinal density gradient (Figure 5-3), increasing stratification and gravitational circulation and increasing the rate of larval transport. Note that this model has not been tested.

Figure B-4: Conceptual Model of the Mechanism for the X2 Effect Based on Gravitational Circulation

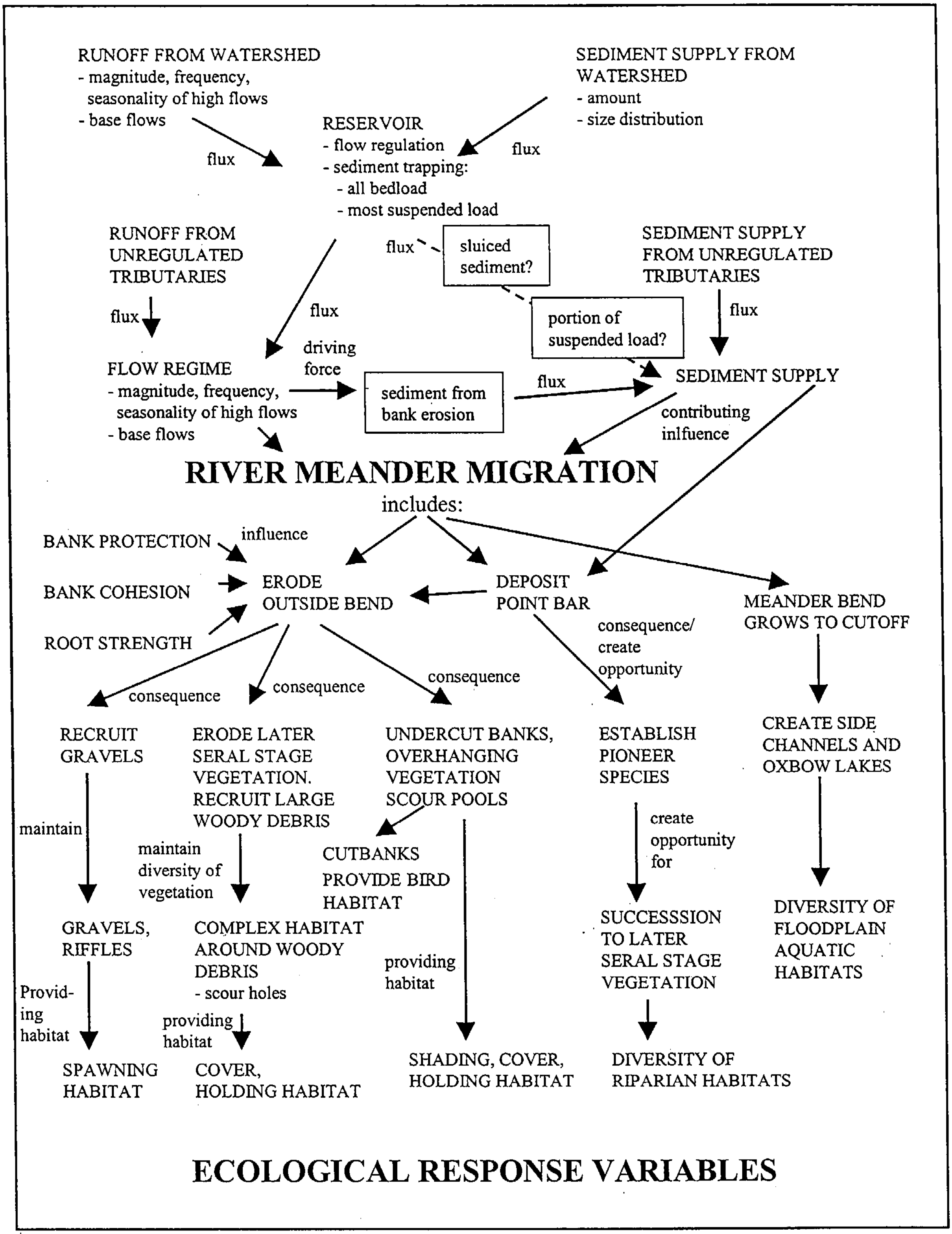
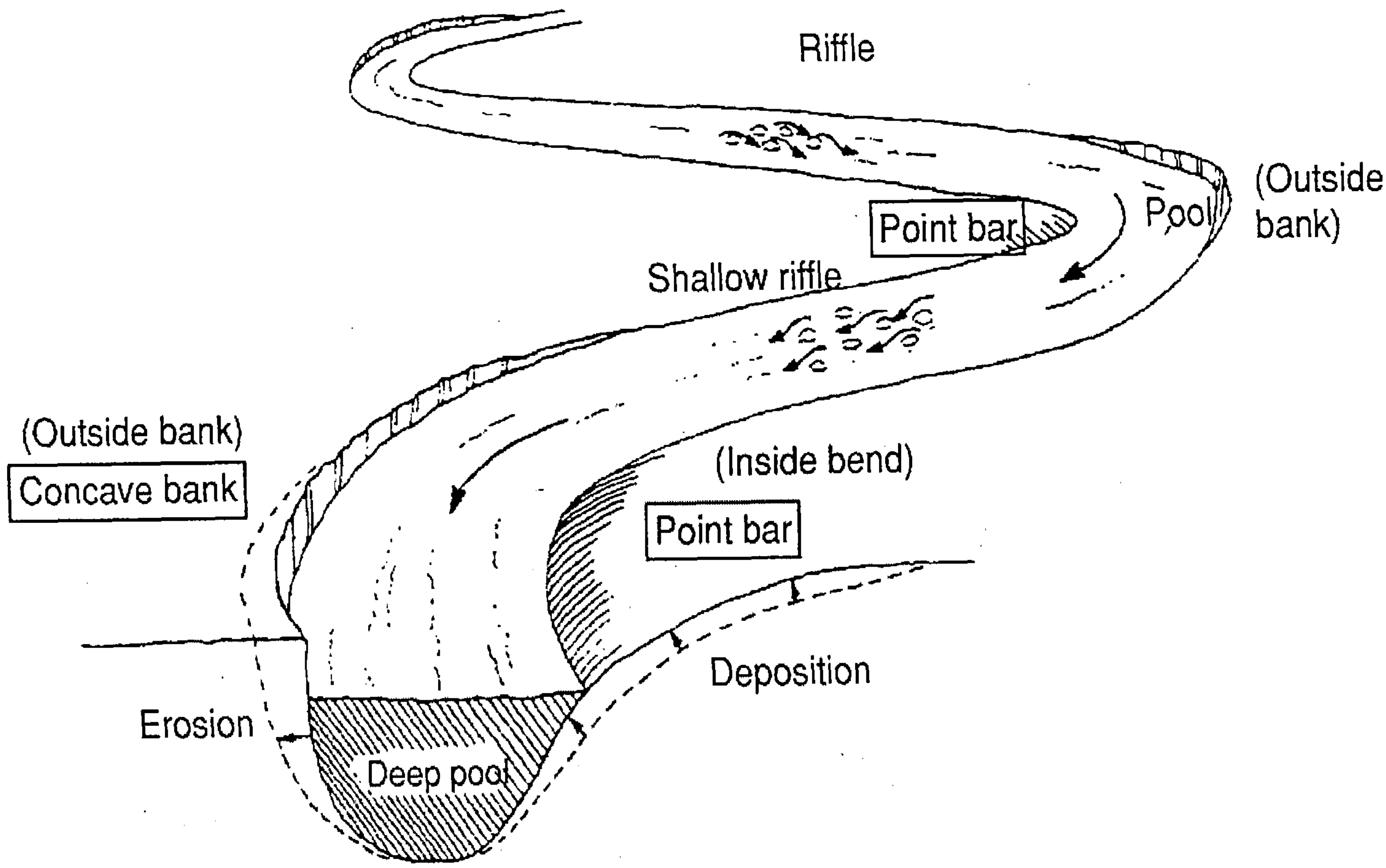


Figure B-5: River Meander Migration Model



Source: California State Lands Commission 1993.

Figure B-6: Diagram of Meander Bend, Showing Variety of Forms (and thus Habitats) Associated with Actively Migrating Meander Bend.

woody debris to the stream, which in turn increases channel complexity through providing cover and inducing scour. On the newly deposited point bar surface, pioneer riparian species establish and undergo gradual succession to species adapted to finer grained soils and less frequent inundation as the surface builds up through overbank sedimentation, which occurs as the channel migrates away from the site. The evolution from point bar to floodplain is accompanied by frequent inundation and a high connectivity with the channel.

Meander migration rate is driven largely by flow and is influenced by sediment supply. In an unregulated river, runoff and sediment load are derived from the watershed and upstream reaches. Below a reservoir, high flows are typically reduced, reducing the stream energy and slowing the rate of the erosion and deposition through which meander migration occurs. The system becomes less active overall although with distance downstream of the dam and increasing input from tributaries, the river typically becomes more dynamic because the effects of the dam are moderated by runoff from the drainage area downstream. Because the reservoir traps all gravel and sand from upstream, sediment supply is reduced, which can lead to channel enlargement as sediment-starved water erodes the bed and banks. Both of these effects are illustrated on the upper Missouri River below Harrison Dam. Rates of erosion and deposition were formerly high and roughly balanced, but after dam construction, the rates of erosion and deposition dropped sharply, and the erosion rates now greatly exceed deposition rates (Johnson 1992).

Management actions can influence meander processes and habitats in a variety of ways. In some cases, high flows can be released from dams to reactivate dynamic channel processes. However, if the high flows are not accompanied by an augmented supply of sand and gravel, the result may be further degrading of the channel and a paucity of gravel deposits. A recognition of the ecological importance of riparian zones (Gregory et al. 1991) and the role of dynamic channel-floodplain interactions (notably meander migration) suggests that restoration of salmon habitat should be undertaken, wherever possible, by restoring the dynamic river processes that create and maintain the desirable habitats.